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A Study of Nonlinear Reflection And Optical Switching In Indium Antimonide

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Abstract

Bistability in the reflected light from an InSb surface has been observed without the use of a resonance cavity, and is explained by an increasing absorption positive feedback mechanism. Relying on this mechanism, we demonstrate a novel InSb optical switch which uses only the surface reflection and operates at room temperature using a pulsed CO_2 laser as the pump beam. The polarity of the switched out signal, the probe beam, was found to depend on the wavelength of the probe beam in the visible and near infrared range. This novel spectral dependence was used to demonstrate several optical logic elements.

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INTRODUCTION

Optical switching which utilizes the optical nonlinearities in narrow bandgap semiconductors can be realized in a variety of ways, such as using optical bistability[1], exciton bleaching[2], optical Stark effect[3], to name the most common effects. Usually the devices based on optical bistability are fabricated as Fabry-Perot resonators, and the bistability arises from a combination of an intensity-dependent refractive index and cavity feedback. The InSb Fabry-Perot resonators require highly monochromatic light near bandgap, and usually require low temperatures for operation. There are several different methods used to obtain optical bistability, and one important method takes advantage of increasing optical absorption[4]. For some nonlinear materials, optical absorption increases when the material is optically excited, resulting in even more absorption. This positive feedback could cause optical bistability without the need of the amplifying effects of a resonant cavity.

In order to realize an optically addressed device while avoiding the disadvantages inherent with macroscopic cavity feedback, it would be desirable to be able to switch using optical reflection from a single surface and using general light sources. Precedent exists for surface reflectivity switching, where the devices used high energy switching light, i.e., photon energy well above bandgap, and the mechanism was via a free-carrier-induced refractive index change[5]. However, most materials were damaged by the giant switching pulse operation that was found to be necessary for the switching.

Recently, we demonstrated a novel InSb optical switch that relies on an absorption feedback mechanism, uses only surface reflection, and displays an interesting spectral

dependence[6]. For a pump-probe configuration, the polarity of the switched out signal was found to depend on the wavelength of the probe beam, and an explanation was proposed. We also reported that this spectral dependence effect is potentially useful for optical logic. In the present paper we extend the previous work to include: the observation of bistable behavior in the reflection of light from the InSb surface, the use of additional wavelength probe beams, a study of the effect of optical alignment on the signal polarity, a demonstration of parallel optical signal processing and a variety of optical logic devices such as OR, AND and NAND gates.

In order to explain the observed bistability with reflected light from an InSb surface, we use an optical absorption feedback mechanism. Consider that the optical absorption in a nonlinear medium is a monotonously increasing function of the photogenerated carrier density as given by:

$$\alpha = f(N) \tag{1}$$

where α is absorption coefficient, and N is free carrier density. For simplicity we assume a steady state between light intensity and N, and that N is linearly proportional to the light intensity, I, and that the carrier life time, τ, is a constant, all of which yields the expression[4]:

$$N = \frac{\alpha I \tau}{h\omega} \tag{2}$$

From this expression it is clear that the more power absorbed in the medium, the more free carriers are generated which results in even more absorption. Thus, this positive feedback loop, will ultimately cause an intensity switching or modulation of the reflection. From

equations (1) and (2) we see that α is a function of N in two ways, namely through N directly and indirectly through I which is related to N. Hence, it is possible to obtain more than one value for α for one value of N, which portends of optical bistability in reflection.

EXPERIMENTAL RESULTS

Optical Bistability of the InSb Surface

In order to demonstrate bistability in InSb, a CO_2 cw laser was used as the light source with adjustable intensity using a SF_6 absorber with adjustable gas pressure. The InSb samples were n-type single crystal slices with one surface polished. A stage cooled by liquid nitrogen was used for these experiments and could keep the sample temperature around $77^{o}K$ inside a small vacuum cell. The incident and reflected light was monitored by a power meter and a pyroelectric detector. Fig.1 shows the experimental configuration.

In the experiment the initial incident light was set at a low intensity, and then increased incrementally in about 100 mw steps, and in another experiment, the incident light intensity was initially set at a high level and then decreased. Fig.2 shows the predicted bistability in the reflected intensity in the form of a hysteresis loop which was repeated several times. Unlike the bistable hysteresis observed in an InSb etalon based on resonant cavity feedback[8], in our present experiment the hysteresis was obtained in an opposite manner, i.e., from a lower to a higher absorbing state. In other words, as the incident intensity increased from a lower level, the reflection increased to a higher state. When the incident intensity was decreased starting from the highly reflecting state, the reflection decreased with a smaller

decrease in the incident intensity than the increase required to reach the highly reflecting state, thereby forming the hysteresis loop.

It should be noted that Wherrett et al previously observed bistability from InSb based on increasing absorption[9], by using a CO laser and an InSb etalon at Brewster's angle to minimize cavity feedback. In our case we used only a single polished surface of an InSb wafer.

Spectral Dependence and External Switching

In this section we examine the spectral dependence of the novel InSb optical switch that relies on the absorption feedback mechanism and uses only surface reflection. We previously reported[6,7] that the polarity of the switched out signal depended on the wavelength of the probe beam. A probe-pump configuration reported earlier[7] was used for the external reflection switching from the InSb surface. The pump beam, was from a pulsed CO_2 laser. The probe beams include visible and near infrared HeNe lasers. The experiments were performed at room temperature using samples of n-type InSb wafers ($N_D = 2x10^{14}$ cm^{-3}) with one polished surface and with wafer thicknesses in the range of 305 μm - 711 μm. The probe beam we initially used was a 6328 Å HeNe laser[7]. The incident angle was tuned slightly off normal and the reflected power from the HeNe laser was monitored by a photomultiplier. Fig 3(a) shows the CO_2 laser pulse and Fig 3(b) shows the reflected signal of the HeNe light which switched out by the CO_2 pulse. The rise time of the reflected HeNe pulse was of the same order of magnitude as that of the CO_2 pulse. A positive reflected signal with a reflectivity change of 25% was observed.

We briefly review our previous report of spectral dependent switching[6]. Depending on the probe wavelength, the reflected signal switched out by the CO_2 pump pulse could be either positive or negative. In addition to the 6328 Å HeNe probe light, we also used the HeNe lasers operated at wavelengths of 5435 Å, 5941 Å, 6040 Å, 6119 Å, 6328 Å, 1.1 μm, 1.5 μm and a GaAlAs diode laser at 8100 Å. A germanium detector was used to monitor the reflection for near infrared light and a photomultiplier for visible light. We also used a pyroelectric detector which has a flat band spectral response to confirm the reflected polarity over the entire range of probe wavelengths. We found that all the reflected probe signals from the visible light were positive, while the signals switched out from 8100 Å, 1.1 μm and 1.5 μm probes were negative relative to the pump beam, and these results are shown in Fig 4. Some of the visible probe lights, such as 5435 Å, 5941 Å and 6040 Å, which from a tunable HeNe laser are not very stable, thus the reflected signals corresponding to these wavelengths (5435 Å, 5941 Å, and 6040 Å) were not as reliable as for the others. The threshold of the pump beam intensity which can externally switch the reflection has been found to be as low as ~ 1 kw/cm^2.

Previously we proposed an explanation for this observed spectral-dependent phenomenon[6] based on an increasing absorption mechanism in which positive feedback arises from both the temperature change and free carrier generation in the medium under optical excitation, and both effects contribute differently to an alteration of the reflectivity. Also, in optical nonlinear materials, such as InSb, the refractive index is intensity-dependent[10] as given in terms of free carriers generated, ΔN, by $n = n_0 + \sigma\Delta N$, where σ is the coefficient of proportionality. Considering that the local temperature increase will

cause an increase in α, σ and n_0, and assuming $d(\Delta N)/dT$ is determined by $d\alpha/dT$, the total thermally induced index change can be written as:

$$\frac{dn}{dT} = \frac{dn_o}{dT} + \frac{d}{dT}(\sigma\Delta N) = \frac{dn_o}{dT} + \Delta N\left(\frac{d\sigma}{dT} + \frac{\sigma}{\alpha}\frac{d\alpha}{dT}\right) \tag{3}$$

Equation (3) implicitly contains the spectral dependence, since n_0, σ, α, dn_0/dT, $d\sigma/dT$, and $d\alpha/dT$ all depend on the wavelength of the radiation. For radiation frequencies, ω, greater than the bandgap frequency, ω_0, σ is a negative value. We may rewrite the equation as follows:

$$\frac{dn}{dT} = \frac{dn_o}{dT} - \Delta N\left(\frac{d|\sigma|}{dT} + \frac{|\sigma|}{\alpha}\frac{d\alpha}{dT}\right) \tag{4}$$

The last two terms inside the parenthesis are positive, thus equation (4) indicates that in a certain spectral range, the change in the reflectivity due to dn/dT could be dominated by the first term on the right side, hence positive; while in other ranges domination could be by the terms inside the parenthesis, and thus negative. The observed spectral dependence can be understood with the use of equation (4). First, the absorption of shorter wavelengths by InSb is much larger at 6328 Å with a k, the imaginary part of the complex index, of 1.79 while k is 0.3 and 0.2 at 1.1 μm and 1.5 μm, respectively[11]. From the relation $\sigma \propto 1/(\omega_0 - \omega)$, where ω_0 is the center frequency of the transition, the optical bandgap frequency[10], infrared light exhibits a larger value of $|\sigma|$ than visible light, since the IR frequency is closer to the central transition frequency, ω_0. Therefore, with a lower k (and α) and a higher σ for 1.1 μm and 1.5 μm light, the last term has a larger value and thus dominates, resulting in a negative value of dn/dT which in turn causes the negative output signal. For 6328 Å light, the last

term is small (with a large α and small σ), so the positive first term in equation (6) dominates, and the result is a positive switched out signal. The pump beam, a CO_2 pulsed laser, excites the InSb sample by generating the excess free carriers ΔN and "writes" the positive feedback which increases the absorption and the temperature in the sample. The probe beams "read" these changes and yield the reflectivity changes as observed. The wavelength of the probe beam determines the sign of the reflected signal.

Equation (4) predicts that, there will be no reflected signal for a wavelength at which positive and negative terms are equal, i.e. thermally induced changes in the index and nonlinear index value are equal. The zero signal wavelength would provide a direct test for our proposed model[6] which is summarized by equation (4). In order to search for and determine this null wavelength, we utilized a ceramic element IR lamp for the IR probe light sources covering the wavelength range from 1 μm and longer, and a Xenon short arc lamp which covers the near UV, visible, to near IR (~ 900 nm). From the IR probe source, a negative switched out signal is observed using the 10 μm pulsed CO_2 pump beam, confirming the negative polarity for the switched out light for the IR probes. For the Xenon lamp as probe, a set of narrow band pass filters was used to select narrow wavelength bands, the pump beam was also from 10 μm CO_2 laser. The experiments showed that under the same experimental conditions, the probe beams with wavelengths of 4047 Å, 4358 Å, 4861 Å, 5461 Å, 5770 Å, 5893 Å and 6560 Å demonstrated similar switching behavior, i.e., they all were switched out with positive polarities, but the signal amplitude from the 6560 Å probe showed a significant decrease in normalized intensity at the detector. Furthermore, there was no signal observed from the 7500 Å probe. However, the detector is relatively insensitive at

this anu ionger wavelengths. The detector used for these experiments was a photomultiplier, since the pyroelectric detector is not sensitive enough for the lamp light. Thus, we can not be sure that for the 7500 Å probe the signal is zero, but it is definitely small. A summary of the signal polarity and behavior for all operating wavelengths is shown on Table 1.

Assuming the null signal does exist, one can define a specific wavelength at which the optical properties of InSb is insensitive to temperature changes. This may important for some optical devices which operate with long duration pulses or thin film structures where temperature can fluctuate.

Alignment Effects on Optical Switching

We found that the alignment between the CO_2 pump beam and the near infrared probe beams is critical, in order to achieve the correct polarity for the reflected signal. Fig 5(a) shows different probe beam alignments relative to the larger spot from the pump beam, and the corresponding reflected signals from a 1.1 μm probe beam are shown in Fig 5(b). With the probe at point C outside the pump area, the reflected signal was positive. This is likely due to a thermal expansion effect where according to the Clausius-Mosotti relation[12], the change in refractive index, Δn, is proportional to the change in local atomic density, $\Delta \rho$. At the center area of the pump beam illumination (point B), the thermal expansion caused by the pump heating decreases the atomic density, hence n decreases. Together with the large negative term in equation (4), the negative Δn gives rise to a negative signal. However, the expansion in the pump beam illuminated region causes a corresponding compression adjacent to region B at C, thereby increasing n and hence resulting in a positive switched out

signal. At the edge area, point A, the negative reflected probe signal is smaller. For the case of the probe beam incident further away from the pump beam, no change is observed in the probe reflection due to the pump beam. With the same alignment conditions for 6328 Å HeNe laser probe, the reflected signal did not change its polarity as the probe beam scanned the illumination area of the pump beam, but the signal intensity was stronger with the probe beam at the center of the pump area than at the edge. The reason for that could be understood once again using equation (4). The linear term dn_0/dT for 6328 Å wavelength is relatively larger, i.e., the index increase due to the temperature increase is larger than the index decrease due to local density decrease which is also caused by a temperature increase. Therefore, the shorter wavelength probe signal was always positive despite the alignment condition.

Since the coefficient of proportionality, σ, has a maximum value when the radiation frequency approaches the bandgap frequency, ω_0, we used a CO laser with a frequency near ω_0, as the probe beam. By using a CO_2 pump laser, we expect more efficient switching of the CO beam. However, the experimental result showed that the CO probe was switched out negatively and about the same magnitude as the 1.1 μm or 1.5 μm probes. Referring to the previous work on InSb[9] and the bistability observed above, the result here indicates that the CO probe beam may only be advantageous at low temperature (77^{o} K), and also may require more careful intensity control in probe beam bias, if one is to make use of the bistable loop.

Optical Signal Processing and Logic

The spectral dependence of the optical switching in InSb is potentially useful for optical signal processing. Assuming that there are two probe beams, one visible and another infrared, then one can envision a scheme where each probe carries separate information. The two probe beams illuminate the InSb surface at the same spot where both are then simultaneously switched by one CO_2 pump beam. Since the switched out signals have different polarities, positive for visible beam and negative for infrared, these signals can be processed in parallel. A demonstration for this parallel processing using 6328 Å and 1.1 μm probe beams and a 10 μm pulsed CO_2 beam as the pump is shown in Fig 6. The spectral dependence can also be used to perform optical logic and for this demonstration a 6328 Å probe beam wavelength was selected. Fig.7(a) shows the experimental configuration in which the 6328 Å laser was used as the probe beam and two CO_2 pump beams are used to provide more control. Fig 7(b) shows the positive going switched out probe signal using both of the CO_2 pump beams separately as an AND gate, and by both pump beams together which displays an OR function. Our previous experiments[6] showed that an infrared probe with one pump yields a NAND gate, and using two pump beams, the device functions as a NOR gate.

CONCLUSIONS

We have investigated the bistable behavior in the reflection of a CO_2 beam from a single InSb surface based on an increasing two photon absorption mechanism. Using the same mechanism, we have demonstrated a novel InSb optical switch having spectral dependent polarity. The main ac' antages of this optical switch are as follows: (1) only surface reflection

is used, i.e. the device does not require a Fabry-Perot type cavity, (2) the signal has a spectral dependent polarity, thus one can choose the output polarity based on the probe beam wavelength and thereby design optical logic functions, (3) the switching takes place at room temperature, and is therefore convenient for applications. The spectral dependence has been utilized for optical signal parallel processing and OR, AND and NAND logic gates have been demonstrated.

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FIGURE CAPTIONS

Fig 1. Experimental set-up used to observed bistability in reflection from an InSb surface. BS is a beam splitter, M is a mirror and A are apertures.

Fig 2. Hysteresis loop in the reflected intensity from InSb showing bistability.

Fig 3. (a) A CO_2 laser pump beam pulse, (b) the reflected HeNe laser probe signal that was switched out by the CO_2 pulse.

Fig 4. A CO_2 laser pump beam pulse and switched out probe laser signals, 500 μs/div. (a) is a CO_2 laser pump pulse, and (b), (c), (d), (e), and (f) are the reflected laser probe beam signals at 1.5 μm, 1.1 μm, 8100 Å, 6328 Å and 6119 Å, respectively.

Fig 5. Different pump-probe beam alignment yields in different reflected signal polarities. (a) shows different beam alignments, and (b) are the corresponding reflected signals.

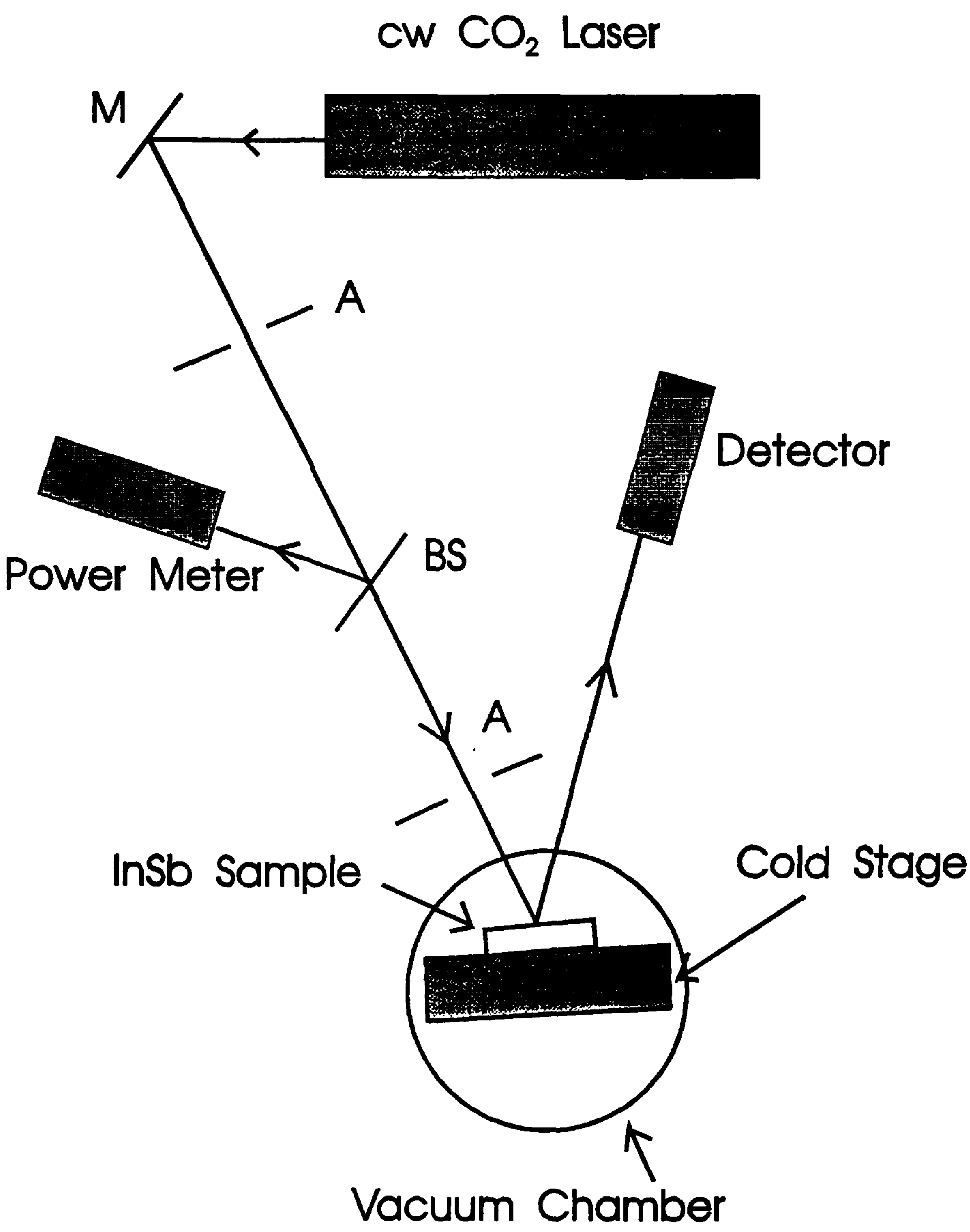
Fig 6. Demonstration of parallel signal processing. (a) is a schematic of a one pump-two probes configuration, and (b) shows reflected 0.63 and 1.1 μm light signals which are simultaneously switched out by one CO_2 pump beam.

Fig 7. Demonstration of an optical OR gate. (a) is a schematic of the OR gate, and (b) shows the switched out probe signals by either of the CO_2 pump beams and by both pump beams.

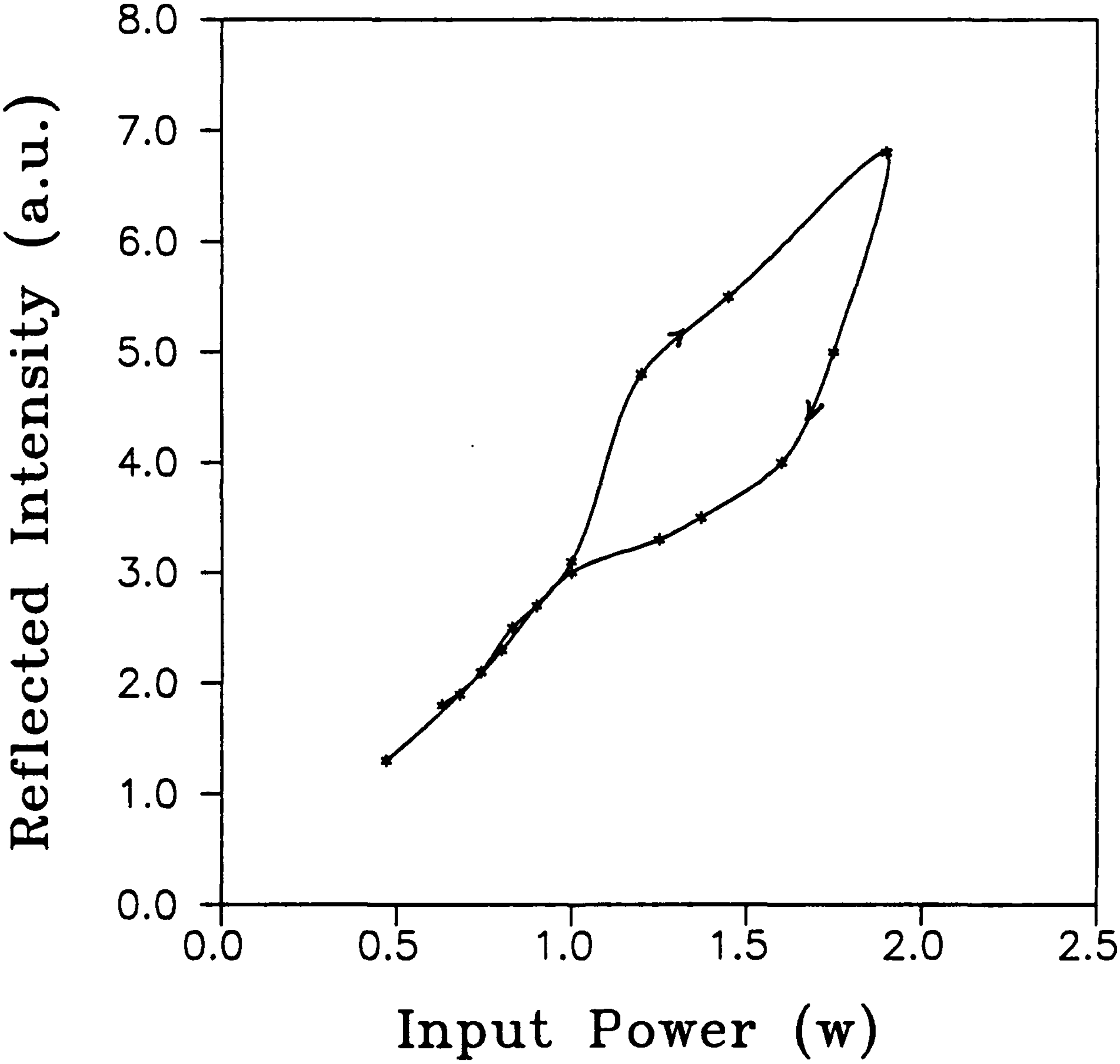
Table 1. Output Signal Polarity as a Result of Different Incident Probe Wavelengths for InSb Using 10 μm Pump Light.

Table 1

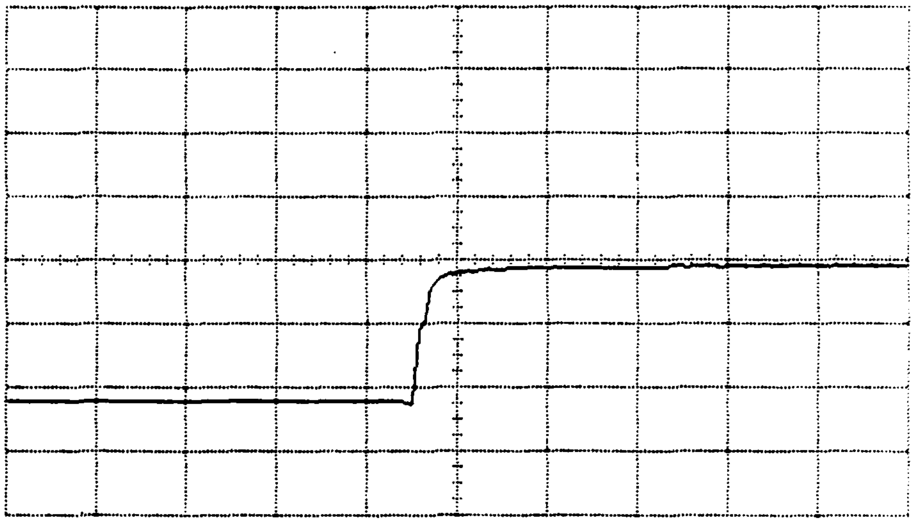
Probe Wavelength	Signal Polarity and Behavior	Probe Wavelength	Signal Polarity and Behavior
4047 Å	positive	6119 Å	positive
4358 Å	positive	6328 Å	positive
4861 Å	positive	6560 Å	positive, weak
5435 Å	positive	7500 Å	no signal observed
5461 Å	positive	8100 Å	negative, weak
5770 Å	positive	1.15 μm	negative
5893 Å	positive	1.52 μm	negative
5941 Å	positive	longer IR	negative
6040 Å	positive		



cw CO_2 Laser
M
A
Detector
Power Meter
BS
A
InSb Sample
Cold Stage
Vacuum Chamber

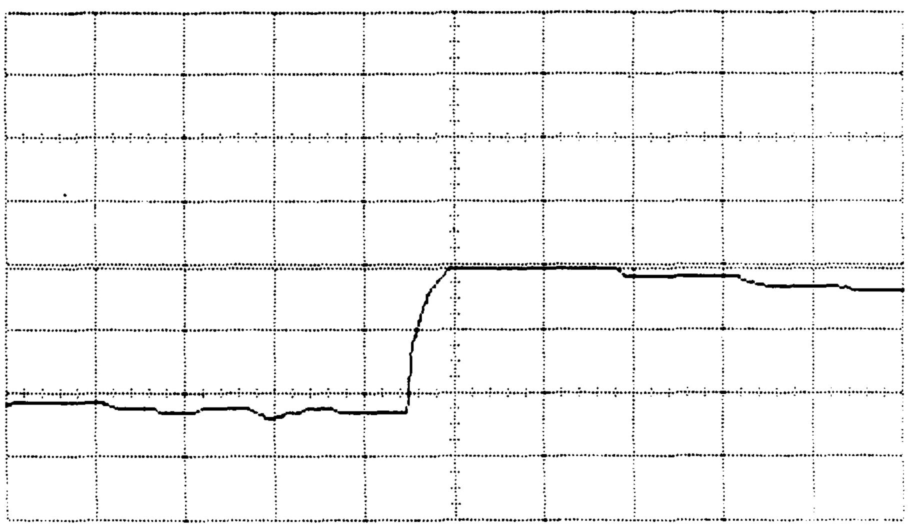


8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.0
0.5
1.0
1.5
2.0
2.5
Reflected Intensity (a.u.)
Input Power (w)



Time (5 μs/div)

(a)



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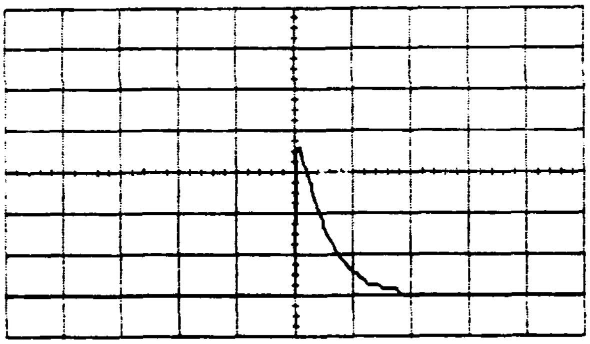

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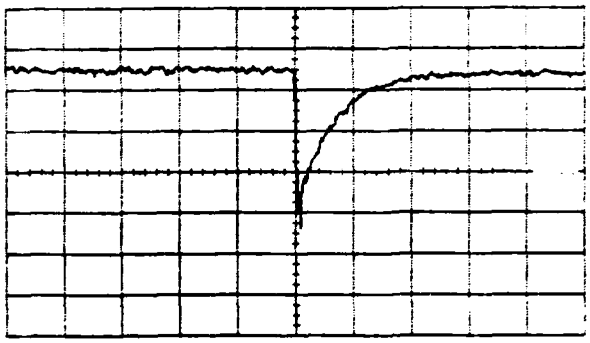

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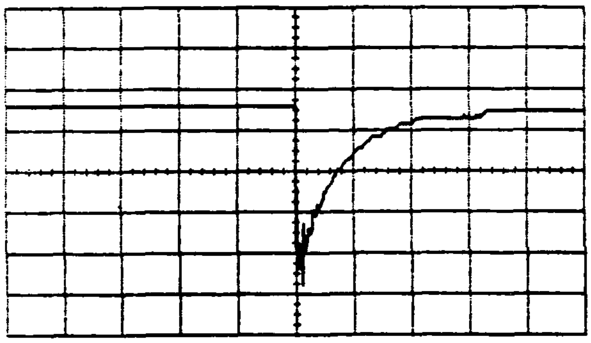

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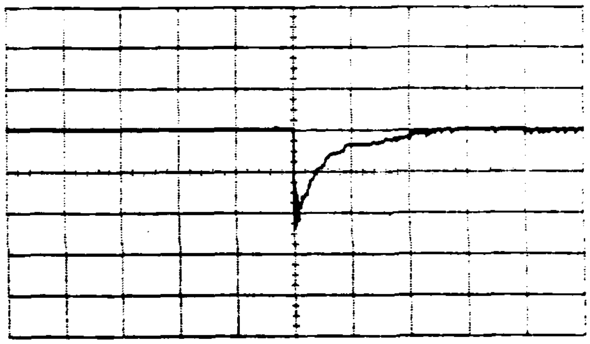

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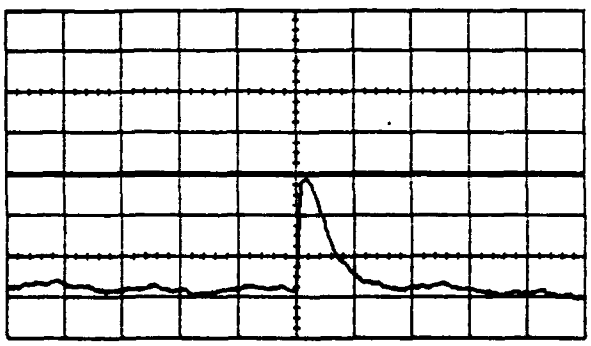

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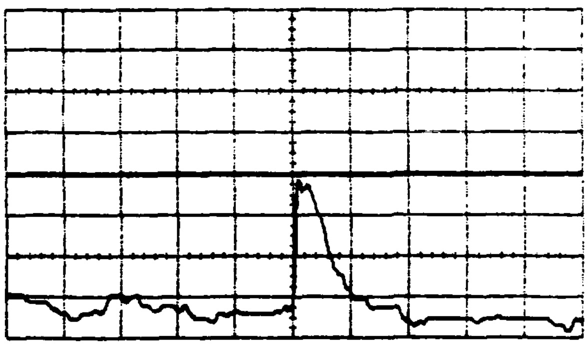

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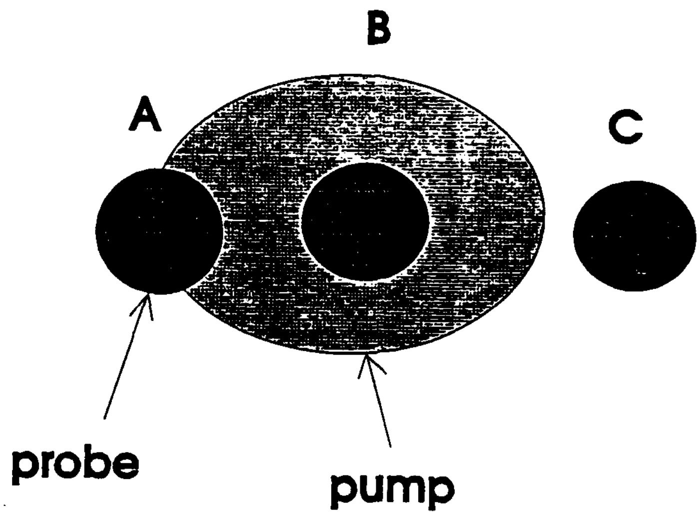

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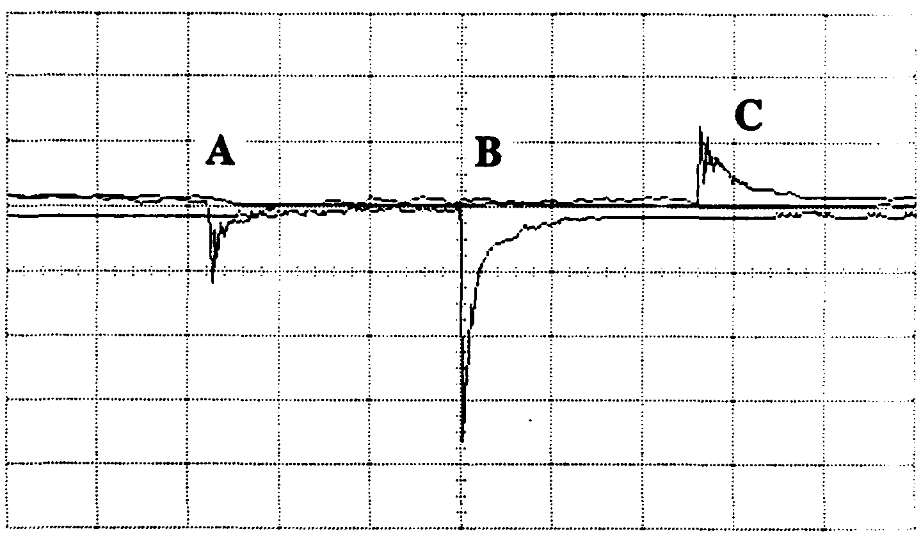

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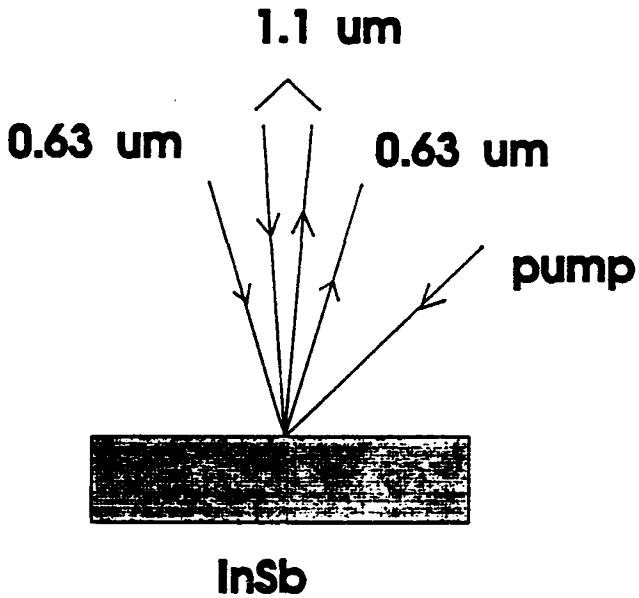

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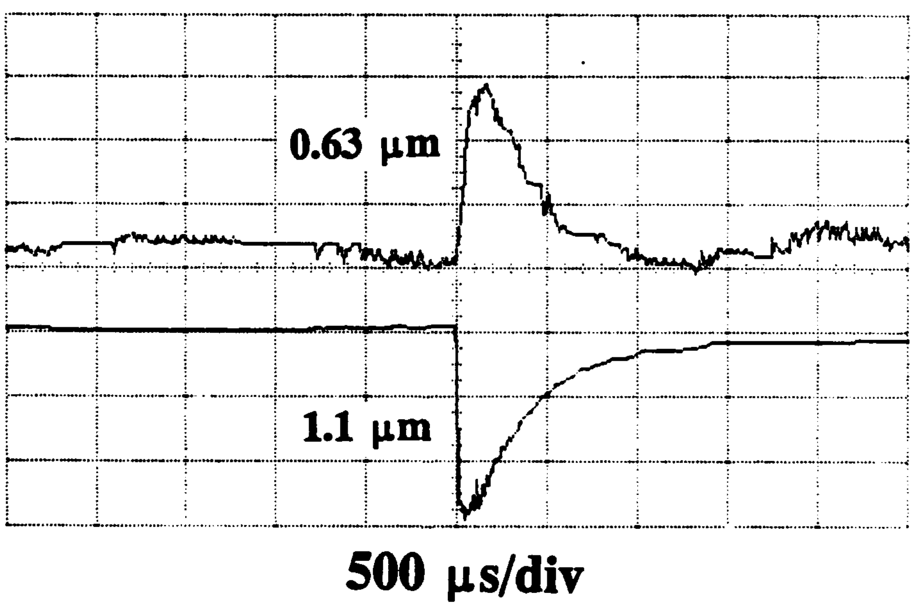

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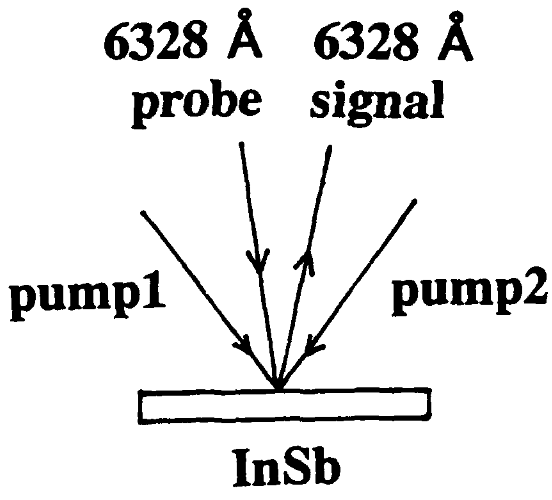
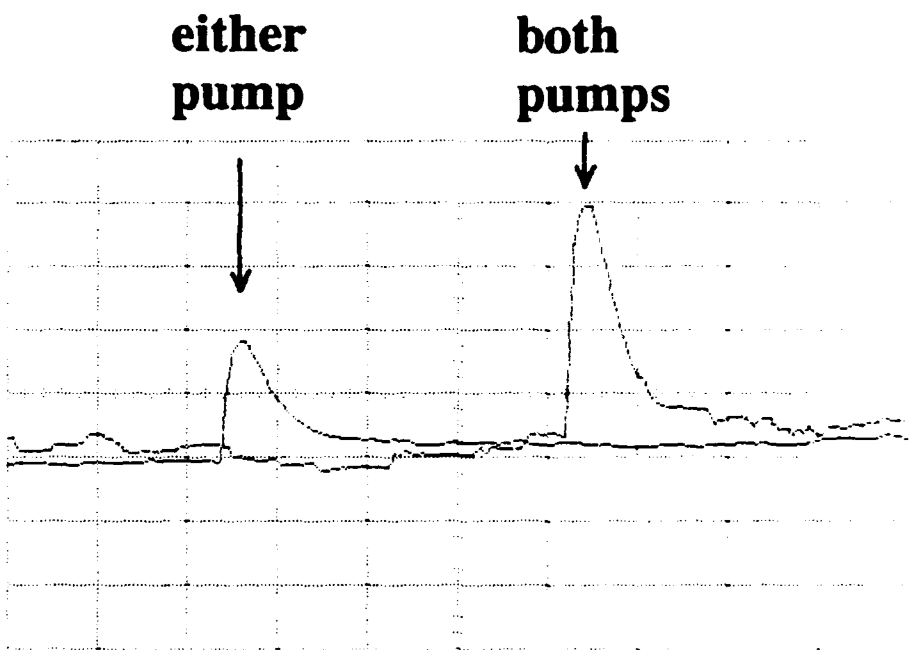

6328 Å
probe
6328 Å
signal
pump1
pump2
InSb

(a)


either
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500 μs/div

(b)